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Signatures for Different PWR Assemblies using Partial Defect Tester (PDET)

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ABSTRACT

The Partial Defect Tester (PDET) produces a unique set of three signatures in Pressurized Water Reactor (PWR) spent fuel assemblies (SFAs) based on normalized neutron, gamma, and gamma-to-neutron signals that are principally dependent on the geometric layout of the guide tubes present in the assembly where the signal measurements are taken. Removal of as few as 10% of pins from an assembly have been shown to be detectable in several simulation studies which have been benchmarked with measurements performed in SFAs. The bulk of the studies conducted so far were performed with the 14x14 type of assemblies. This study expands the applicability of the PDET methodology to other type of SFAs such as 16x16 or 17x17 assemblies which also show symmetric signatures that are principally dependent on the quadrant symmetric layout of the guide tubes. The signatures from these larger assemblies also show that diversion of as few as 10% pins can be detected using PDET. In addition, in the interests of economy, this study examined the possibility of using fewer than all the available guide tube locations in a SFA, thus reducing the number of detectors needed, and still be able to detect diversion. At this time the conclusion was that more studies would be needed to ensure the feasibility of this approach and that, for now, it would be useful to have measurements at all locations and have all the data possible to ensure detection of diversion.

INTRODUCTION

Various attempts have been made in the past two decades to develop a technology to identify a possible diversion of pins and to determine whether some pins are missing or replaced with dummy or fresh fuel pins. However, to date, there are no safeguards instruments that can detect a possible pin diversion scenario that meet the requirements of the IAEA. The FORK detector system [1-2] can characterize spent fuel assemblies using operator declared data, but it is not sensitive enough to detect missing pins from spent fuel assemblies (SFAs). Likewise, an emission computed tomography system has been used to try to detect missing pins from a SFA [3]. This has shown some potential for identifying possible missing pins but the capability has not yet been demonstrated, especially in an inexpensive, easy to handle setting for field applications.

A novel methodology has been developed to detect partial defects in PWR spent fuel assemblies without relying on any input from the operator. The prototype being built is known as the Partial Defect Tester (previously also referred to as the Partial Defect Detector), PDET. The methodology involves inserting tiny neutron and gamma detectors into the guide tube locations, measuring the signals and processing them to form normalized signals of the neutron and gamma responses and the gamma-to-neutron ratios. Earlier papers detailed the development of this unique signature that will be noticeably perturbed if some of the fuel pins are replaced with dummy pins both in isolated SFAs as well as SFAs in an in-situ condition in the storage racks in symmetric or random removal patterns [4, 5, 6]. The methodology was validated with measurements in SFAs with excellent agreement between the experimental and simulated data [7].

The bulk of simulations performed to develop the methodology used 14x14 type SFAs since these were available for testing in a state that was essentially intact (only one pin missing) as well as states with clustered and random missing pins to the tune of 11-12% of the total. In the following sections, simulations performed with 16x16 and 17x17 assemblies will establish signatures for these product lines. Results of a sensitivity study to determine if fewer than all the available guide tube locations can be used to perform measurements and still be able to detect diversion at the lower threshold of approximately 10%.

COMPUTATIONAL MODEL

Two product lines that are commonly in use, with 16x16 and 17x17 fuel pin arrangements, were modeled based on SFAs from operating reactors. The 16x16 model had an average burnup of 35.4 MWd/kg with pin-by-pin burnups mainly in the range 35-36 MWd/kg. The 16x16 type of fuel has 20 guide tube locations and a central instrument tube, thus having 235 active fuel pins per assembly. The 17x17 model had an average burnup of 52 MWd/kg with much larger range of burnups from 45-56 MWd/kg. The 17x17 type of assembly has 24 guide tube locations and a central instrument tube, thus having 264 active fuel pins per assembly. Single SFA models were used to develop the base signature for each type.

The source terms for the gamma and neutron signals were obtained using ORIGEN-ARP [8]. The MCNP [9] calculations were performed in the fixed source mode using the latest available ENDF/B-VI data sets [10]. Two separate runs were made: a coupled neutron-gamma run using the neutron source terms and gamma run using the gamma source term. It must be noted that the neutron induced gamma contribution is negligible in these situations compared with the fission product decay gammas. Neutron and gamma fluxes were obtained at the guide tube locations where the measurements would be made. All relevant results had standard deviations of less than 0.5%. Figure 1 shows the MCNP generated input models for the two types of SFAs.

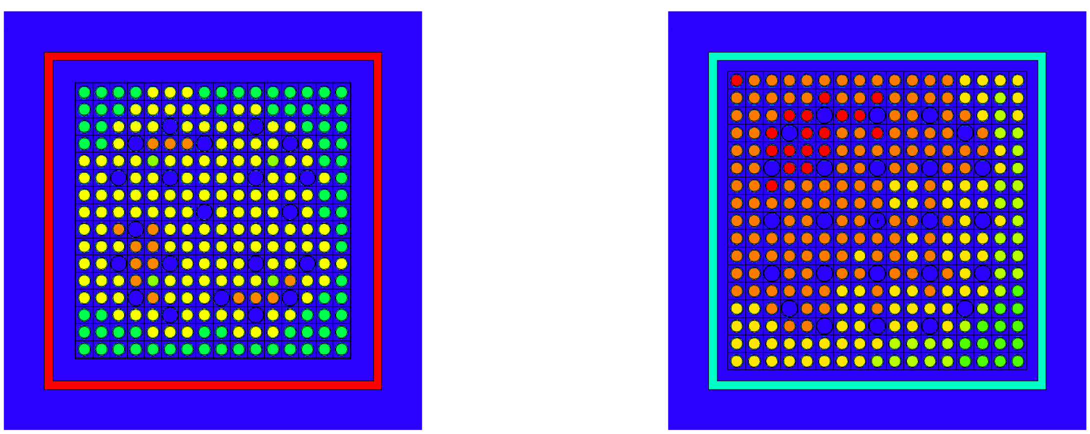

Figure 1. Spent Fuel Assembly: 16x16 (left) and 17x17 (right)

ANALYSIS OF A 16 X 16 ASSEMBLY

The base case with no missing fuel was first simulated to determine the baseline signature for this type of SFA. Following this, a case was simulated with 22 missing pins distributed all over the assembly. This pattern was present in the actual assembly where the pins were removed for testing. Figure 2 shows the layout of this assembly with the missing pins. As in the case of the 14 x 14 assembly, a counterclockwise scheme for each set of five guide tube locations was followed in plotting the signatures. The pattern involved for the 16 x 16 assembly would be K6, I4, K3, M4, N6, etc. as seen in Figure 2. The three signatures consisted of the thermal neutron signal (< 0.4 eV), gamma signal, and the gamma-to-thermal neutron signal each set normalized to the maximum signal among them. Figures 1 and 3 show the three sets of signatures for the baseline as well as the case with the missing pins.

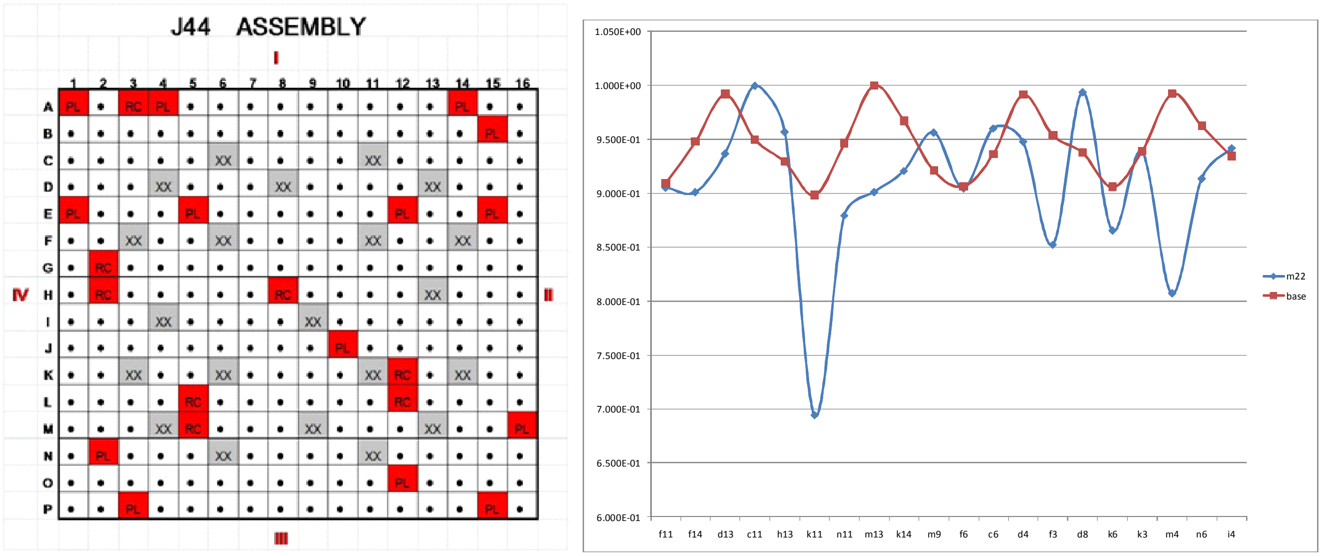

Figure 2. 16 x 16 SFA with 22 Missing Pins (left) and Ratio Signature for Baseline and 22 Missing Pins

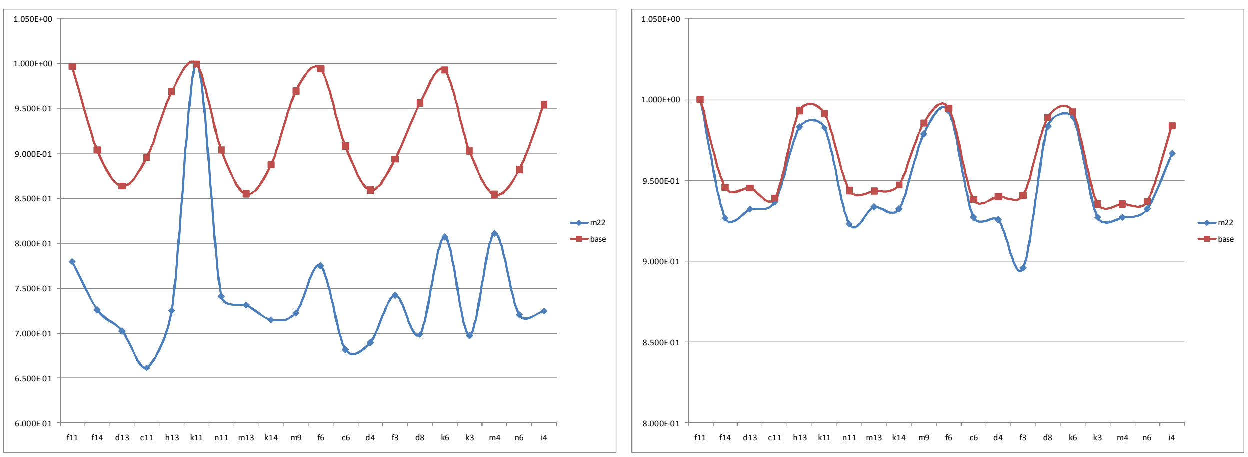

Figure 3. Thermal Neutron (left) and Gamma (Right) Signatures for Baseline and 22 Missing Pins

From Figures 2 and 3 it is clear that the baseline signatures show a symmetric pattern while the case with 22 missing pins, representing only about 9% of the total active pins, shows clear diversion. This is especially true for the neutron signature and as a result the ratio signature. The guide tube location at K11 shows the typical spurt in the thermal neutron signal since it is adjacent to three missing pins. Location M4 has two missing pins adjacent to it and also shows a spike. The gamma signature is rather invariant when compared to the baseline.

ANALYSIS OF A 17 X17 ASSEMBLY

The 17 x 17 assembly was modeled both with the detailed intra-assembly burnup profile as well as with a uniform 51 MWd/kg burnup. Figure 4 shows the profile of missing pins in the SFA from the operating reactor. The sixteen missing pins represent a mere 6% of the total active pins and falls below the goal of the 10% or higher detectability threshold. However, it would be instructive to examine the sensitivity of the methodology to this semi-clustered set of missing pins. The plotting scheme for the guide tube locations is L6, L3, N4, O6, I9, O9 etc. Figure 4 also shows the baseline and diverted signatures for the gamma-to-thermal neutron normalized ratio. Figure 5 shows the neutron and gamma signatures.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
A	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	RC
B	●	RC	●	●	●	●	●	●	●	●	●	●	●	RC	●	RC	●
C	●	●	●	●	●	XX	●	●	XX	●	●	XX	●	●	PL	RC	●
D	●	●	●	XX	●	●	●	●	●	●	●	●	●	XX	●	●	●
E	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
F	●	●	XX	●	●	XX	●	●	XX	●	●	XX	●	●	XX	●	●
G	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
H	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
I	●	●	XX	●	●	XX	●	●	XD	●	●	XX	●	●	XX	●	●
J	●	●	●	●	●	●	●	●	●	●	●	PL	●	●	●	●	●
K	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
L	●	●	XX	RC	●	XX	●	●	XX	●	●	XX	●	●	XX	●	●
M	●	●	RC	RC	●	●	●	●	●	●	●	●	●	●	●	●	●
N	●	●	●	XX	RC	●	●	●	●	●	●	●	●	XX	●	●	●
O	●	●	●	●	RC	XX	●	●	XX	●	●	XX	●	●	RC	●	●
P	●	●	RC	PL	RC	●	●	●	●	●	●	●	●	●	●	●	●
Q	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●

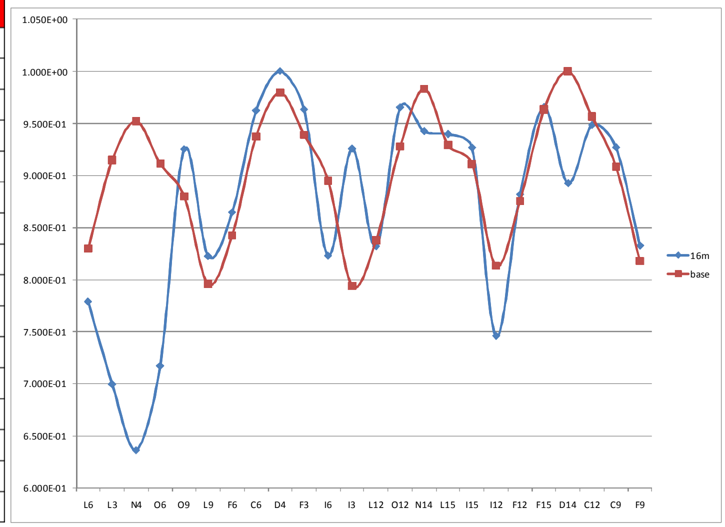

Figure 4. 17 x 17 SFA with 16 missing pins (left) and Ratio Signatures for Baseline and 16 Missing Pins

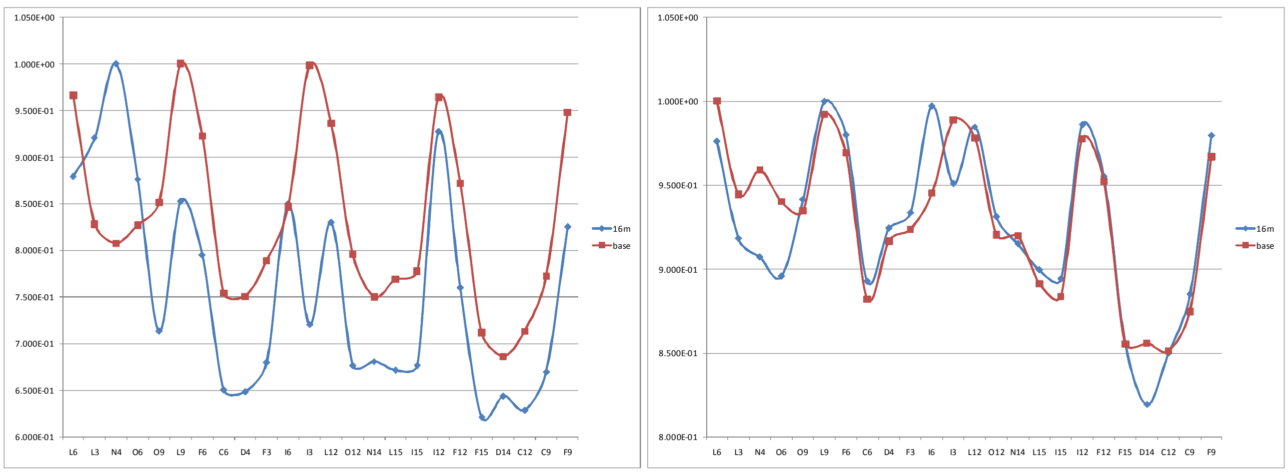

Figure 5. Thermal Neutron (left) and Gamma (right) Signatures for Baseline and 16 Missing Pins

The baseline signatures show a tilt, particularly for the gamma signature, because of the intra-assembly burnup gradient. The baseline gamma signature shows small peaks at N4, D4, D14, and N14 since these locations have contributions from more pins than their neighbors, L3, O6 etc. The overall signature exhibits a symmetric shape with the tilt caused by the burnup gradient. In the case of the missing pins, as expected, the position N4 sees a high thermal neutron signal while the more localized gamma sees a drop in the signal owing to the cluster of missing pins in the vicinity. Thus the relative ratio of the two signals drops steeply whereas the baseline would see a peak. From the three signatures it is clear that even for this small amount of diversion the signatures change visibly from the baseline.

A very difficult case would be one with completely uniform burnup and a symmetric diversion as shown in Figure 6. In this case, thirty pins, representing approximately 11% of the total active pins, are missing from the center of the SFA in a symmetric manner. In a more realistic diversion scenario, the diverted fuel pins would be replaced with pins made of a material like stainless steel.

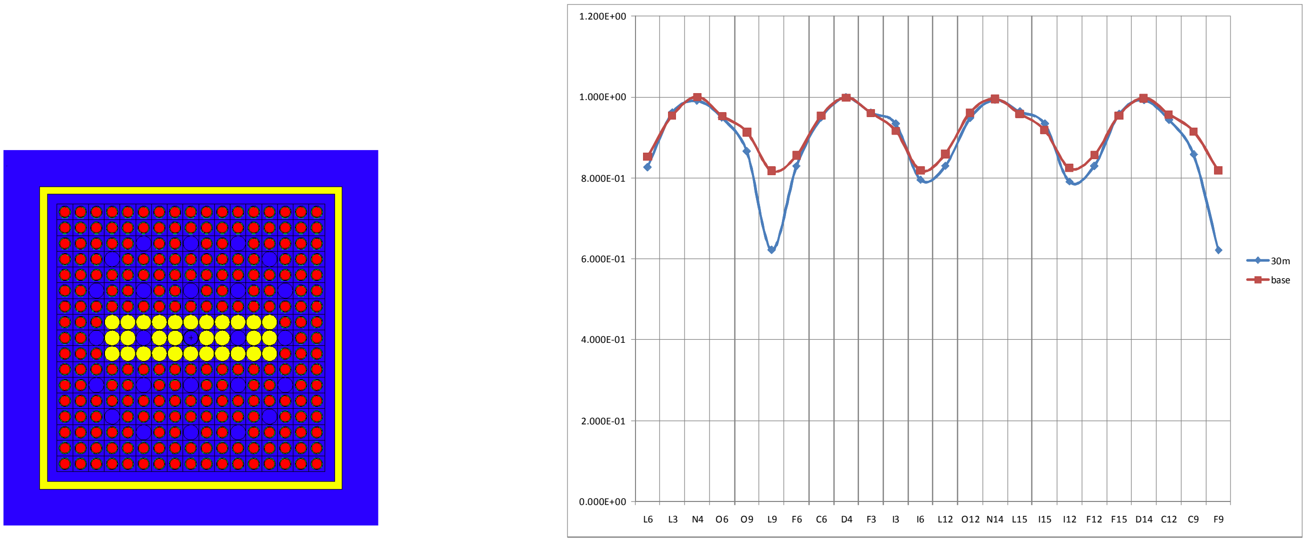

Figure 6. Schematic of 30 Missing Pins (left) and Ratio Signature for Baseline and 30 Missing Pins

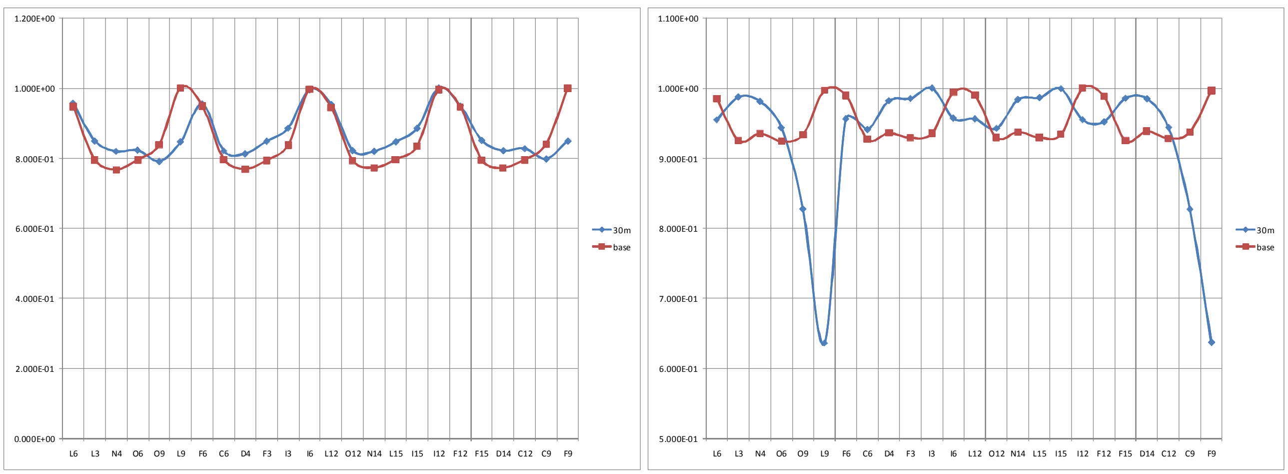

Figure 7. Thermal Neutron (left) and Gamma (right) Signatures for Baseline and 30 Stainless Steel Dummy Pins

In this case with uniform burnup and symmetric diversion, the neutron signature shows little variation from the baseline. However, the gamma signal shows clear distortion from the baseline. It must also be observed that the baseline gamma signature here shows a centerline symmetric shape as the baseline signature in the previous case shown in Figure 5 without the tilt caused by the burnup gradient. The two centerline locations closest to the center of the SFA, L9 and F9, see a sharp drop in the signal because they have lost the contributions from the center pins. The drop is less for their neighboring locations on the center line, O9 and C9. As a result of these changes in the gamma signal, the ratio signature sees a more than normal peak to valley ratio at L9 and F9. Typical peak-to-valley drops are less than 0.2 [5, 6] while in this instance there is a drop of 0.4. This is a secondary indication of diversion [5, 6] even though the overall shape remains intact, being smoothed over by the neutron signal contribution at each location. Thus, all three signatures need to be examined to detect diversion.

SENSITIVITY OF SIGNATURES TO THE NUMBER OF GUIDE TUBES USED

It is also of interest to examine the possibility of using fewer guide tube locations to perform measurements and still be able to detect diversion. This would reduce the number of detectors needed and the cost of the instrument. Since the product lines all have the four clusters each with 4 guide tube locations at each quadrant, the possibility of eliminating 8 locations (I3, I6, I12, I15, C9, F9, L9, and O9) that form the cruciform set of guide tube locations (see Figure 8) was studied for the 17 x 17 case. The case discussed in the previous section with uniform burnup and the symmetric removal of 30 pins was used to test the feasibility of this approach. This case will be an extreme test since at least six of these eight eliminated locations would be most affected by the missing pins.

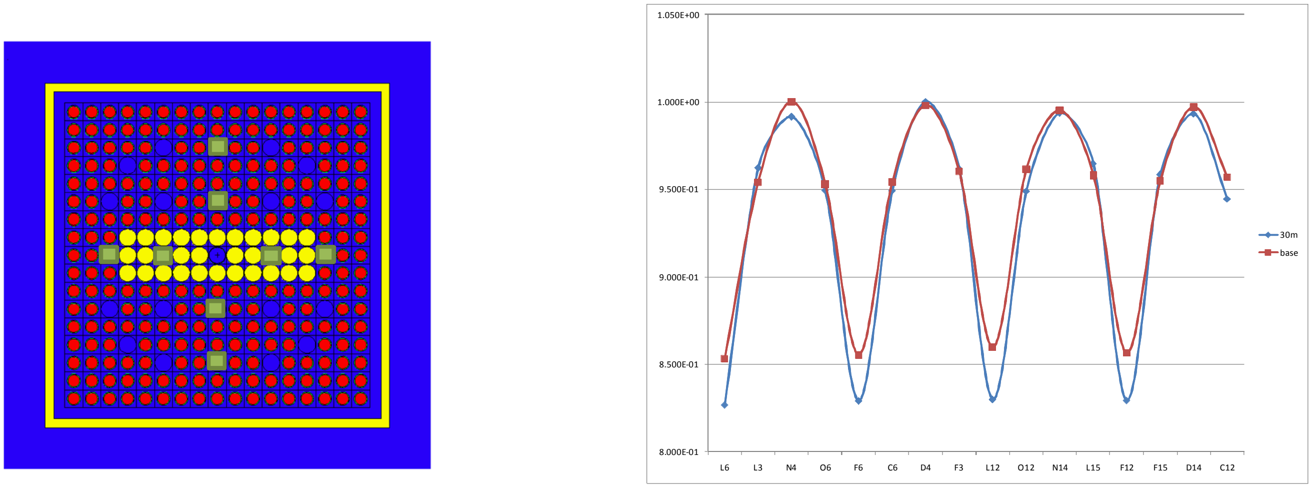

Figure 8. 17 x 17 SFA with Guide Tube Locations not used (left) and Ratio Signature for Baseline and 30 Missing Pins

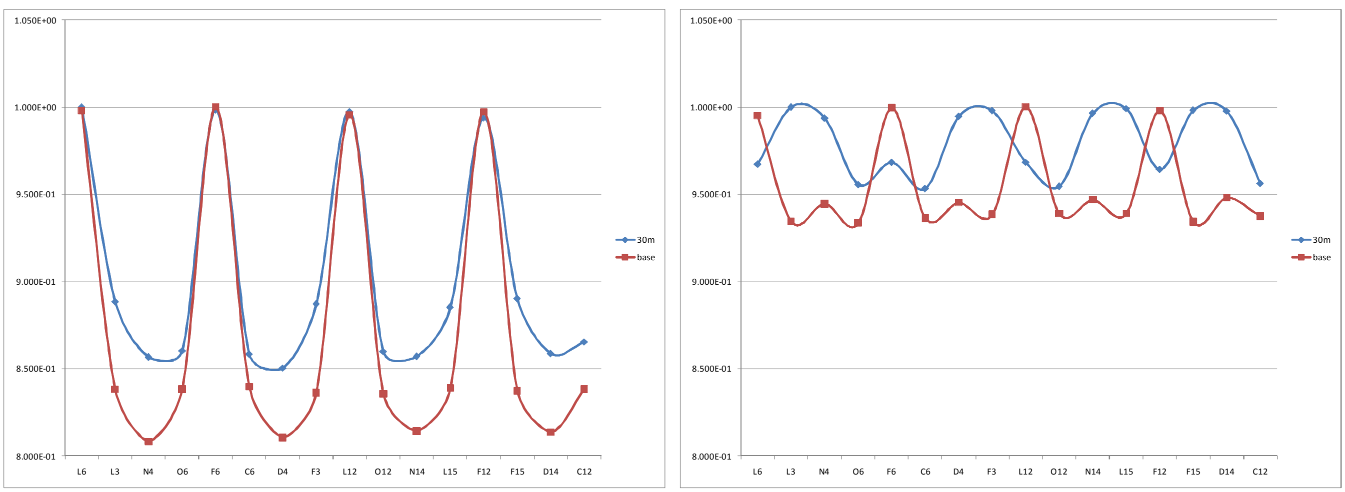

Figure 9. Sixteen Guide Tube Thermal Neutron (left) and Gamma Signatures for Baseline and 30 Missing Pins

Examining Figures 8 and 9, it is clear that the ratio and neutron signatures do not show the diversion when the 8 guide tube location are omitted. The gamma signature shows the diversion with a different pattern for the diverted signature. However, at this time the conclusion was that more studies would be needed to ensure the feasibility of this approach and that, for now, it would be useful to have measurements at all locations and have all the data possible to ensure detection of diversion.

CONCLUSIONS

As a result of extensive modeling that has been validated with measured data in SFAs from operating reactors, a breakthrough methodology has been developed for partial defect detection in PWR fuel that is sensitive to detecting as few as 10% missing pins in a symmetric or random pattern. This far exceeds the commonly accepted IAEA goal of detecting 50% or more missing pins from an assembly. The baseline signature is principally dependent on the geometric layout of the guide tubes in the various PWR product lines. For sparsely distributed missing pins typically the neutron and ratio signatures are more useful in indicating diversion. For symmetrically distributed missing pins at the lower threshold of detectability of around 10%, the gamma signature is the reliable indicator of diversion. For larger fractions of missing pins, all the signatures will clearly show diversion. In addition, a drop of more than 0.2 from peak to valley in the signature constitutes as secondary indication of diversion.

The methodology is being implemented in a field usable tool for partial defect verification that does not rely on any operator provided data and can be used with the fuel in an in-situ condition. The mechanical design of the prototype tool has been completed [12] and the signal and data processing is being implemented. The tool promises to fulfill a long standing need for detecting partial defects in spent fuel.

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